Fallback level concepts for conventional and by-wire automotive brake systems

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Abstract: Brake-by-wire represents the replacement of traditional brake components such as pumps, hoses, fluids, brake boosters, and master cylinders by electronic sensors and actuators. The different design of these brake concepts poses new challenges for the automotive industry with regard to availability and fallback levels in comparison to standard conventional brake systems. This contribution focuses on the development of appropriate fallback level concepts. Hardware-in-the-loop (HIL) techniques and field trials will be used to investigate the performance and the usability of such systems.

Key words: Brake-by-wire, Fallback level, Hardware-in-the-loop (HIL), Field trial

1. Introduction

The last three decades of automotive design have mainly been influenced by x-by-wire-technologies. Besides steer-by-wire and throttle-by-wire a major aspect in developing driving dynamics was and still is the brake-by-wire technology, e.g. the Electro Mechanical Brake (EMB) and the die Electro Hydraulic Brake (EHB). The first implementation of the brake-by-wire technology in the automobile history was the EHB system of the Japanese automotive supplier ADVICS (subsidiary of Toyota) at the beginning of the year 2001 in the Toyota Estima Hybrid. In September of the same year the first EHB system SBC (Sensotronic Brake Control) of the world´s largest automobile supplier BOSCH was presented at the International Motorshow at Frankfurt (IAA) [1].The SBC was implemented in the Mercedes-Benz S- and C-Class and in the luxury car brand Maybach. Several performance problems of the electro-hydraulic brake system forced Mercedes-Benz to recall 680.000 cars of the E-Class and SL-Class in May 2004. Further difficulties arose from the low performance of the mechanic-hydraulic fallback level of the SBC system [2]. The Mercedes and Maybach drivers simply did not accept the fallback level concept of SBC in spite of the fact, that it was designed to match the legal regulations with a minimum deceleration of 2,44 m/s^2 at a pedal force 500 N. The wide range of customer complaints in the end forced Mercedes Benz in the year 2005 to the biggest recall (1.3 million units) in automobile history [3]. The tremendous loss of image has been influencing the design of electronic brake systems by OEM`s and suppliers ever since. The availability and design of fallback levels of different brake-by-wire systems has been a heavily debated subject since that day.

2. Legal requirements for brake systems

The registration of a motor vehicle is generally regulated in every single country in the world. The most important rules for the automotive industry originate in the USA and in Europe. The Japanese regulations have also a great significance. However, Japan has explicitly acknowledged most of the European regulations as equivalent, by acceding to the United Nations Economic Commission for Europe (UN-ECE) Agreement in 1958. Therefore, the focus of the following details is on the American and European legal requirements and standards [1]. In general, the definition of a brake system is described as follows: A brake system comprises a control device, transmission means and the brakes. The control is always that device, through which the driver issues his brake request by providing a signal which controls some form of energy in the transmission. The device may be a brake-pedal, a manual lever or, in some parking brake systems, an electrical switch. The transmission is a term used for all parts, between the control and the brakes which transfer the brake request, thus resulting in a brake actuation. This may include a booster, master-cylinder, ABS or ESC, valves and brake-pipes and/or hoses. The brake is the element where the friction components are clamped, thus generating the brake force in order to decelerate the vehicle [4] [5]. According to the ECE R 13H and FMVSS 135 regulations, the minimum performance of the service brake is defined as follows:

- V= 100 [km/h]
- foot force = 500 [N]
- deceleration = 6,43 [m/s²]
- max. stopping distance = 70 [m]

The secondary brake system is per definition the brake system which comes into effect when the service braking system is in failure mode:

- V= 100 [km/h]
- foot force = 500 [N]
- deceleration = 2,44 [m/s²]
- max. stopping distance = 168 [m]

3. Fallback levels of automotive brake systems

The definition of brake-by-wire is based on the fact that the brake actuation device is decoupled from the rest of the brake system [6]. The service brake of a brake-by-wire system has the same working method as the hydraulic power brake. The mandatory demand of common brake system regulations for brake-by-wire systems with an electro mechanical transformer is the redundant power supply. For this type of brake-by-wire architecture (for instance EMB) there is no hydraulic or mechanical fallback level provided. For brake-by-wire systems with a hydraulic mechanical transmission, as well as for standard brake systems, hydraulic or mechanical fallback levels are possible [1]. Brake systems of this category must fulfill the minimum requirement of the secondary brake system regulation.

The common understanding of a fallback level for brake systems is the brake performance which a brake system achieves in the case of a partial system failure. There are many different kinds of failures for conventional and brake-by-wire systems as well as corresponding legal requirements and the regulations by law are given, but ever since the SBC disaster the driver's acceptance is the most important factor for new fallback level concepts of automotive brake systems.

4. First Results of A Test Drive Series

The dimensioning of a brake system is incomplete if the impact of the driver, which means in this case the brake as the contact center between human and machine, is disregarded [2]. For the complete braking process of the driver a large number of scientific papers are available [3], but the impact for the driver in case of a sudden and unforeseen changeover into the specific brake pedal characteristic of certain fallback levels has not been intensively investigated. Only the investigation: Driver´s perception of a secondary brake system of the United Kingdom Department for Transport [7] aims in the same direction. That there is only insufficient detailed knowledge to this specific topic available also came up quite recently in a simple test drive at Continental. One notably measurement of a test person will be discussed in the following to clarify this context.

The procedure of this internal test run was that the proband drives at first with functional service brake system, in order to adapt to the test track. The main driving task for the test drive was a spot brake maneuver in each round on the testing ground. After two rounds on the test track the instructor on the passenger seat could activate the fallback level mode with a manual switch (Figure 1) unnoticed from the driver.

Figure 1. Manual fallback level switch.

In order to explain the measurement data sheet in Figure 2 the braking process is divided into three phases. The measured values are deceleration (black), brake pedal travel (purple), brake pedal force (red), wheel speed (blue) and the wheel pressure, i.e. the pressure in the hydraulic system, of all four wheels (green).

The **phase I** starts with the activation of the fallback level from the passenger unnoticed from the driver shortly before the spot brake maneuver. The first stage ends with the first touch of the brake pedal from the test driver, which is also marked as zero point of the timeline. As you can see in **phase II** the proband has applied the brake system until 1400 ms and achieved a deceleration of 0,23 g at a pedal force of 161,12 N. In spite of the fact, that the driving task was not fulfilled at this time, the proband has interrupted the braking process. **In phase III** the test driver tried to brake again according to the variable course of the pedal travel and pedal force. During the whole data recording of the brake maneuver, this proband achieved only a reduction of the wheel speed from approximately 2 kph and a maximum wheel pressure of 18 bar, therefore missing the spot, where the car should have come to a stop [8]. What was the reason for this brake interruption? Over the reasons and the effecting interactions for the drivers brake maneuver interruption can only be speculated upon. From the perspective of the authors: This open question should be the starting point for a specific scientific investigation in the area of fallback level designs of tomorrows automotive brake systems. The main task in such an investigation is to find out what fallback level setup is acceptable and manageable for a normal driver. Which technical parameters influences the failure mode condition of brake systems regarding brake pedal travel, brake pedal force and free travel in combination with the appropriate achieved deceleration? Furthermore, are technical measures possible which increase the acceptance of the failure mode?

In addition of the technical design, the investigation shall determine, if the acceptance of a fallback level is also influenced by the attributes which are necessary for the general driving task. These are age, gender, driving experience and the individual traits of the proband [2].

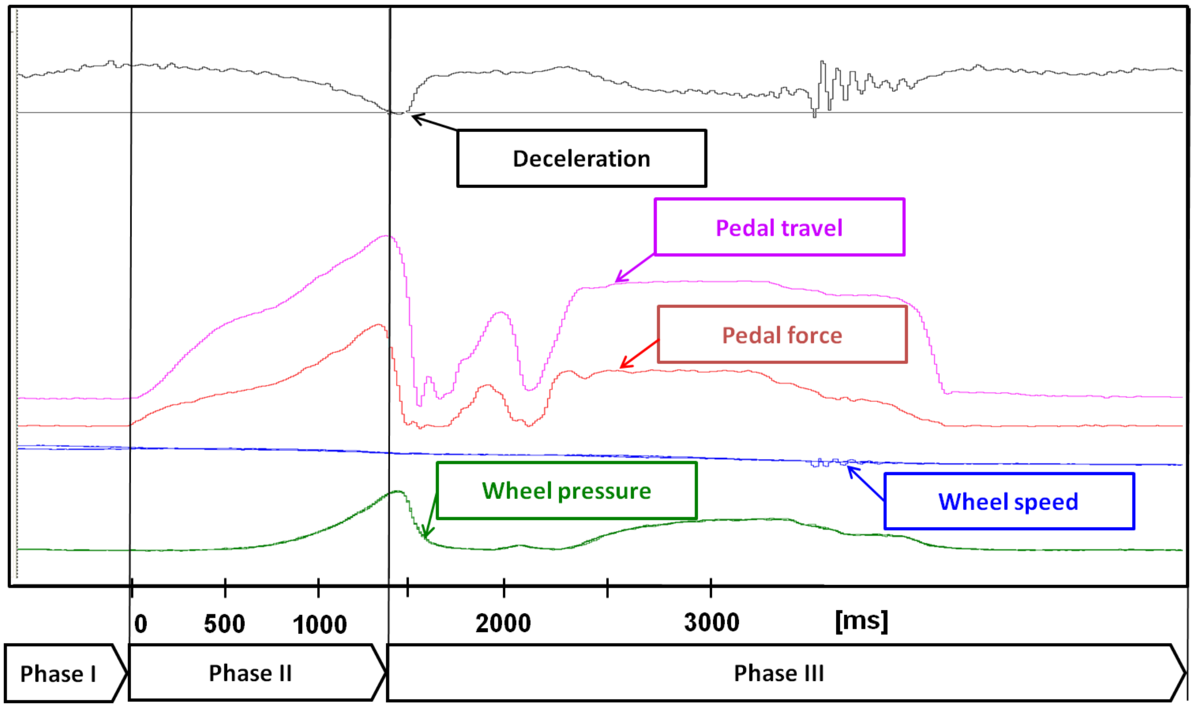

Figure 2. Measurement-Example of a test driver after changeover into the fallback level.

To answer the open questions the international automotive supplier Continental has already implemented a research project. This current project includes the two major areas:

- FMEA Research & Simulation
- Large scale of Test Drives

which will be introduced in the following chapters.

5. Simulation set up

The first step is to find out on basis of existing failure mode and effects analysis (FMEA) of different automotive brake systems the typical fallback level modes and their influences at the brake pedal characteristic. In the next step the top events of the investigated failure modes will be simulated on a test bench that is currently being established. The main use of such test benches is to test software functions, but it allows also to simulate different malfunction setups which automotive brake systems could have [9]. This planned hardware in the loop (HIL) environment will be able to simulate and display a wide range of different brake pedal characteristics regarding pedal travel, pedal force and free travel. The main components of the test bench design are the hydraulic valve block with integrated tandem master cylinder (TMC) and pedal angle and pedal force sensor. The experimental setup includes also a car seat with quick release to represent the normal seat position of the driver. The common failure mode of hydraulic leakages and electrical short-circuits can be illustrated at the HIL. The main requirement of the test environment is, to give the proband the nearly real experience of the brake situation in a automobile, but the failure modes which were investigated at the simulation have the disadvantage that the deceleration forces are missing. As a consequence of this fact, the simulation results can only be used for a classification which brake pedal characteristics of pedal travel, pedal force, free travel are not necessary to use for the dynamic test drive setup. Nevertheless, the results will reduce the possible combinations of possible fallback levels which will not fulfill the acceptance of the driver.

6. Test Drive Setup

After the feedback of the simulation test, there is a field trial with a large number of test drivers with a suitable track layout for the execution planned. The test drive concept has to bear in mind that it has to be rolled out in different areas of the world, to investigate if there are regional differences on the attributes of the probands possible. The elaboration of the test drive setup should be reproducible in terms of the technical characteristics of the test vehicle. Therefore the current standard measuring configuration of Continental is also used for the test drive setup (Figure 3).

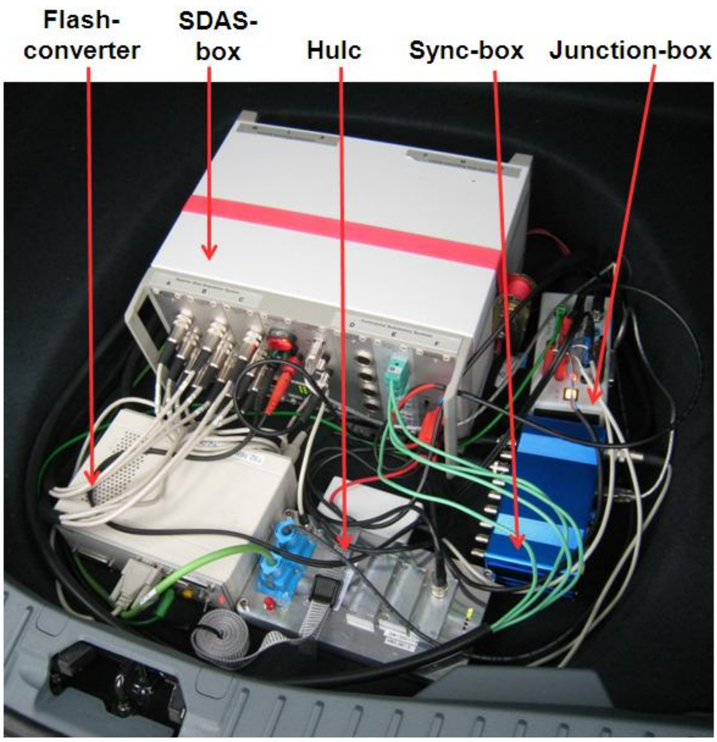

Figure 3. Recording of the braking process.

This setup includes a Flash-converter, SDAS-Box, Hulc, Sync-Box and a Junction-box. The Flash-converter with K-line connection is used in this experimental setup to flash software into the ECU of the electronic brake system. The SDAS-Box (Superior Data Acquisition System) is needed for the analogue or CAN signals interaction. The Hulc device is a Continental in-house development. As the first box in the ECU data stream, the Hulc converts the raw data stream form the ECU to a standard protocol ("XCP") on USB. The Sync-Box is used for the syncronisation between the CAN and FlexRay vehicle network. The Junction-box is responsible for the power supply in the measurement setup. The measurement software for recording, configuration and analysis is Datalyser a proprietary software of Continental, which is normaly installed on notebooks of the vehicle test engineers (Figure 4).

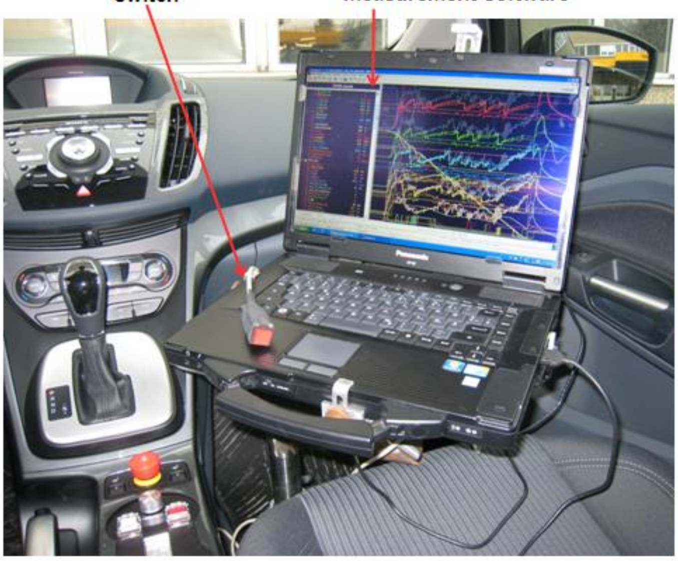

Figure 4. Notebook with Datalyser Software.

7. Conclusion and Outlook

Right now, the area of fallback level design is oblique of the experience of the engineering staff of the car manufacturer and brake system supplier. There are many different interpretations of the might best possible fallback level dimensioning being discussed. The regulations by law are well recognized and marking the minimum requirement of the brake system design, but on the other hand these regulations are not answering the question if the fallback level of the brake system will be accepted by normal drivers later on. The current scientific results in the area of the driving dynamics are not helpful as a reference for the acceptance of a normal driver for a specific brake pedal characteristic in a failure mode. The brake system supplier Continental is working on this new scientific field and a pre-development project has been started. This project will include a HIL Simulation and a large scale of test drives. After completing this project, the statistical results should be useful for current and future brake system designs at Continental.

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